Plans for ARM Research 2000-2001

1. Principal Investigator Information

Robert G. Ellingson
Department of Meteorology
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2. Title of Research Grant

A Study of Longwave Radiation Codes for Climate Studies: Validation with ARM Observations and Tests in General Circulation Models

3. Scientific Goal(s) of Research Grant

As noted in the attached progress report, the long-term research goals of this project are to

- develop an optimum longwave radiation model for use in GCMs that has been calibrated with state-of-the-art observations for *clear and cloudy* conditions
- determine how the longwave radiative forcing with an improved algorithm contributes relatively in a GCM when compared to shortwave radiative forcing, sensible heating, thermal advection and convection.

The specific plans for 2000-2001 are to continue the ongoing research discussed in the attached progress report, namely:

- Develop and use a technique for inferring a variety of cloud parameters from sky imagery at the ARM sites.
- Extend and test our longwave cumulus parameterization for eventual GCM implementation (i.e., theoretical cloud-radiation studies).
- Test GCM layer cloud overlap assumptions and finite-size cloud-radiation parameterizations in a single column version of the MM5 mesoscale model.
- Develop and use a technique to estimate aerosol properties from whole-sky imager data.
- Extend the longwave QME to develop a longwave data set for distribution to the international ICRCCM community.

The attached progress report describes the ongoing activities in each of these areas. Please note that three of the areas encompass parts of student dissertation research, portions, but not all, of which will be completed during 2000-2001. Additional details are available upon request.

PROGRESS REPORT ON ARM RESEARCH 1999-2000

1. **Principal Investigator Information**

Robert G. Ellingson
Department of Meteorology
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College Park, MD 20742

2. **Title of Research Grant**

A Study of Longwave Radiation Codes for Climate Studies: Validation with ARM Observations and Tests in General Circulation Models

3. **Scientific Goal(s) of Research Grant**

In 1990, 1993 and 1996, we proposed to DOE to contribute to the goal of improving the treatment of radiative transfer in GCMs under clear-sky, general overcast and broken cloud conditions by attacking major problems connected with one of the dominant radiation components of the problem - longwave radiation. In particular, our long-term research goals are to

- develop an optimum longwave radiation model for use in GCMs that has been calibrated with state-of-the-art observations for *clear and cloudy* conditions
- determine how the longwave radiative forcing with an improved algorithm contributes relatively in a GCM when compared to shortwave radiative forcing, sensible heating, thermal advection and convection.

Our plans for 1999-2000, which will continue in 2000-2001, are to

- develop and use a technique for inferring a variety of cloud parameters.
- extend and test our longwave cumulus parameterization for eventual GCM implementation.
- test GCM layer cloud overlap assumptions.
- extend the longwave QME to develop a longwave data set for distribution to the international ICRCCM community.

4. **Accomplishments**

- Discovered large discrepancies between pyrgeometer/AERI inferred and theoretical estimates of effective longwave cloud fraction for many broken cumulus cases at the SGP. The results are consistent with an overestimate of the absolute cloud fraction by the MMCR and the BLC and/or an underestimate of the cloud opacity, both of which have serious implications to scientific and programmatic applications of ARM data.
- Developed a procedure for estimating probability of clear line of sight through the atmosphere from WSI and TLCV data for use in validating/developing techniques for including finite sized cloud effects on longwave transfer.
- Discovered a theoretical improvement for including finite sized cloud effects on longwave fluxes and cooling rates.
- Obtained and have begun to use a single column version of the MM5 mesoscale model for the purpose of performing sensitivity studies of cloud averaging and finite sized cloud effects.

- Developed a procedure for tracking the intensity of individual stars seen in WSI data, with the goal of using clear-sky WSI data for estimating aerosol optical depth during the nighttime.
- Developed and made available new tools for longwave radiation calculations.
- Worked with IRF working group to define a broadband QME for testing GCM radiation parameterizations.

5. Progress and accomplishments during last twelve months

Science Progress and Accomplishments

- *Analysis of SGP longwave radiation and cloud data*

  Over the last two years, Ms Zhouhui Cheng (student) and Dr. Ezra Takara (post-doc) have carefully examined pyrgeometer, AERI, MMCR and BLC data for single-layer cumulus cases at the SGP site during 1997. Using the time-coherence technique for estimating longwave effective cloud fraction N_e developed by Han and Ellingson (2000 – see below), they found several days during which the inferred value of N_e is often greater than a factor of 2 less than what would be calculated from different N_e models using MMCR or BLC data as input (0.3 or more in cloud fraction). The differences imply a combination of overestimates of the absolute, opaque cloud fraction by the vertically viewing instruments and the modeled cloud opacity. We understand that there may be some insect contamination of the MMCR data, although we do see similar effects when using the BLC. The results imply that there are many cases of rather thick broken cumulus that are far from black or that the MMCR estimates of absolute cloud fraction can not be trusted for broken cloud conditions. Both of these implications are very important for scientific and programmatic applications, because N_e errors of this magnitude can lead to overestimates of the downward longwave flux at the surface of the order of 30 W m^{-2} - a LARGE error! Thus, the resolution of the discrepancies tops our agenda for the coming year. We hope to be able to identify the various effects by incorporating analyses of MWR liquid water path and the WSI/TLVC data discussed below. A PowerPoint file with figures and descriptions of this research entitled RGE_EET.ppt may be downloaded from http://metosrv2.umd.edu/~bobe/downloads .

- *Estimation of finite-sized cloud properties from the WSI and TLCV*

  A basic quantity necessary to calculate the transfer of longwave radiation in the presence of broken cloudiness is the probability of a clear line-of-sight, P_{clear}, through the cloud field. Individual images from the whole sky imager (WSI) and the time lapse camera video (TLCV) provide near instantaneous information on the angular (azimuth and zenith) distribution of cloudiness. Time series analyses of these data can provide the necessary probability distribution function. However, the roughly 8-minute interval between WSI images is generally too coarse to be able to provide good cloud statistics over the roughly 10-min. time period necessary for inferring N_e from pyrgeometer data using the Han and Ellingson (2000) time coherence technique. However, when a digital, QuickTime, version of the TLCV data became available, one of our students, Yingtao Ma, developed a technique to use the video to obtain the required statistics.

  Briefly, the TLCV images are recorded in QuickTime format at about 8-second intervals. Each image is easily decomposed by IDL into red, green and blue components. The red to blue ratio for each pixel for a given cloud image is compared to the same ratio for a clear-sky image to determine the presence or absence of cloudiness (following a procedure similar to that developed by Tim Tooman for the WSI). Since the angular position of each pixel is known, each 10-minute period yields roughly 75 instances of fractional cloud cover for each pixel within each 2π ring surrounding about 60° of zenith. Integrating over azimuth yields the azimuthally averaged P_{clear} or alternatively, the cloud fraction as a function of zenith angle. This quantity can be compared directly with model estimates given information of the absolute cloud fraction (available from the zenith measurements), the cloud aspect ratio, and spatial distribution information, all of which may be estimated from other ARM data.

Ma has developed the software to process the TLCV and WSI data, and he has applied it to one 16-minute period during 1999. For this particular day, he found that P_{clear} from the WSI and TLCV agree well with each other, but it did not monotonically decrease with zenith angle as predicted by different models. This later feature indicates, and the pictures show, a spatially non-uniform distribution of cloud elements for this period - more cloud at zenith than away from zenith. This may well be a partial explanation of the discrepancies noted above, but it obviously requires considerable additional analysis. Ma will be performing this analysis as part of his dissertation research. A PowerPoint file with figures and descriptions of this research entitled rge_ytm.ppt may be downloaded from http://metosrv2.umd.edu/~bobe/downloads .

- *Theoretical cloud-radiation studies*

The analysis used in our recent papers (e.g., Han and Ellingson 1999) for estimating cloud effects on P_{clear} have interpolated between the nearest neighbor clouds and use an asymptotic limit at large angles. As part of his dissertation research, Ma has shown that this interpolation is unnecessary, because one can determine an analytic expression that covers both limits. This result will be tested along with other models using the TLCV/WSI data analysis technique described above.

Interpretation of the time series of the various ARM cloud observations (e.g., MMCR, BLC, WSI, TLCV, etc.) is a major issue for all ARM scientists, because each measurement gives a different, and often confusing, element of the cloud field. We've begun to look at the sampling issue during the past year by using Monte Carlo simulations of simple cloud fields and advecting them over stationary instruments to simulate what might be seen. Although such simulations are helpful, real cloud statistics are necessary for an adequate analysis. Takara and Ma will extend this analysis during the next year by using cloud fields generated by cloud resolving and ensemble models.

- *Single Column Model Studies*

Our research is geared toward the development, validation, and testing of radiation models for use in general circulation models. The testing of such models in GCMs, particularly for cloud effects, is not straightforward and can be very computer time consuming. Thus, we have decided to go to an intermediate route of using a variant of a single column model (SCM). Most of the ARM SCM activity has been focused on using GCM parameterizations on a large column surrounding the SGP central facility (the order of 200 km on a side). This smears out the cloud scale, and one is forced to parameterize the cloud effects in terms of the large-scale variables. In doing so, one must chose the procedure for horizontally averaging cloud effects. One way to check these results is to use a subset of smaller columns in which the clouds are prescribed more explicitly. The larger scale average can be computed as the mean of the individual cells, and this can be compared to the average one might obtain from using a large-scale parameterization using different cloud overlap approximations.

As a first step towards involvement in this activity, we have obtained a single column version of the MM5 mesoscale model from the University of Washington. Mark Armstrong, a graduate student supported by this project, is learning how to use the model, and he will be performing a variety of cloud experiments using our finite size cloud models and different cloud overlap assumptions as part of his dissertation research. We plan to work closely with Ric Cederwall and other members of the ARM SCM community to develop these experiments, and next year we plan to involve Dr. Dalin Zhang, a UMD faculty member and an expert on MM5, with these experiments.

- *Aerosol estimation from WSI data*

WSI images are recorded 24 hours a day, and Tim Tooman has developed a technique to estimate nighttime cloudiness from these data using known star brightness and position data. Since each star moves during the night, tracking the intensity and position of each star with time can provide a Langley plot for each star. If starlight were monochromatic, an analysis of the calibrated WSI images could yield literally hundreds of Langley plots each night from which one could estimate aerosol optical depth, perhaps even as a function of time. However, since the light is broadband, models must be used to interpret the observed radiance in terms of aerosol optical depth. Since the brightness of each star is related to its emitting temperature, radiation models can be used to infer a small amount of information on the spectral distribution of the aerosol effects.

Ms. Ileana Musat, one of the three students supported on this grant, has developed IDL software to track the positions and intensity of individual stars on consecutive WSI images as part of the development of a Ph.D. dissertation prospectus. She plans to develop this technique to obtain multiple Langley plots for clear-sky nights from which to infer aerosol optical depth with the use of model calculations. Such a technique will help fill a void in the SGP aerosol data, as there is not currently a direct technique to determine aerosol optical depth at night. Although aerosol estimation is not the primary thrust of this project, this type information is necessary to interpret the longwave AERI and pyrgeometer data, and it adds perhaps another tool to interpret the aerosol returns from the SGP Raman lidar.

- *Tools for longwave radiation calculations*

A computationally fast, easy-to-use, desktop available, accurate spectral radiation model is required for many scientific and educational purposes (e.g., IOP planning, instrument checks, climate change simulations, what if analyses, etc.). We've attempted to meet these needs over the last two years by developing graphical user interfaces (GUIs) for a 10 cm^{-1}, LBLRTM-calibrated code previously reported by us at ARM meetings (see below Warner and Ellingson, 2000). The model calculates the spectral, angular, and vertical distributions of longwave radiance and the vertical distributions of integrated fluxes and cooling rates using user specified distributions of atmospheric gases and clouds. The GUI allows the user to specify the atmospheric parameters, to save selected numerical output, and to graphically portray the results of the calculations. A user may also selectively eliminate individual gases, specify constant concentrations and/or choose isothermal conditions. Other features allow simple sensitivity analyses. GUIs have been developed for Power PC Macintosh® computers and for IDL® -equipped workstations with a FORTRAN 90 compiler. The software may be obtained at http://metosrv2.umd.edu/~bobe/MDTERP and at http://metosrv2.umd.edu/~ezra. A publication describing the model is in preparation for *BAMS*.

- *IRF Broadband QME*

  The longwave portion of ICRCCM has been slowed by the failure of the water vapor working group to come to closure on the error bounds on low level water vapor. Nonetheless, the IRF believes the errors are now known well enough to produce a longwave broadband QME for use in checking climate model radiation codes. Our group helped plan the protocol for this analysis, and we expect this to begin about the time this report is submitted. During the next year, we plan to develop a web-based mechanism for involving the international community to use the QME data to test their longwave climate models. This will be followed by an ICRCCM workshop in 2001 to summarize the results.

Programmatic and/or Professional Accomplishments

- *Delivered and/or Prepared Several Presentations ARM-funded Research, including:*

  Ellingson, R. G., 1999: The Accuracy of Longwave Radiation Calculations for Earth-Atmosphere Applications. IUGG Meeting, Birmingham, UK, July 26-30, 1999.

  Ellingson, R. G., 1999: Thermal Radiative Transport in Clouds. International Workshops on Intercomparison of 3-dimensional Radiation Codes: I3RC-99 - First Workshop: November 17-19, 1999, Tucson, AZ.

  Ellingson, R. G., and E. E. Takara, 2000: MDTERP MarylanD TErrestial Radiation Package: A Narrow-Band Longwave Radiation Model with a Graphical User Interface. ARM Science Team Meeting, San Antonio, TX, 13-16 March 2000 and EUMETSAT Users Meeting, Bologna, Italy, May 29-June 30, 2000.

  Ellingson, R. G., D. Han, and Z. Cheng, 1999: Validation of Cumulus Cloud Parameterizations for Longwave Radiation Calculations. IUGG Meeting, Birmingham, UK, July 26-30, 1999.

  Ellingson, R. G., T. Tooman, T., J. Shields, D. Sowle, G. Christensen, and S. Moore, 1999: Automatic Determination of Daytime and Nighttime Cloud Fraction. IUGG Meeting, Birmingham, UK, July 26-30, 1999.

  Ma, Y., and R. G. Ellingson, 2000: Probability of Clear Line-of-Sight Determined from the VTLC and WSI. ARM Science Team Meeting, San Antonio, TX, March 13-16, 2000.

  Takara, E. E. and R. G. Ellingson, 1999: Longwave Broken Cloud Approximations Allowing for Cloud Transmission. AMS Conference on Atmospheric Radiation, Madison, WI, June 22-July 2, 1999.

  Takara, E. E., and R. G. Ellingson, 2000: Validation of longwave cumulus cloud parameterizations using ARM data. ARM Science Team Meeting, San Antonio, TX, March 13-16, 2000.

- *Led and/or Participated in Several Science Team Activities, including:*

  1. As chair of the Science Team Executive Committee, organized and led several meetings of this group.
  2. Organized, with Joe Michalsky, the ARM IRF Working Group Workshop (October 1999).
  3. Acted as Mission Scientist for ARESE II February-April 2000.
  4. Represented the ARM Science Team at several AMT meetings.

5. Developed, with Tony Clough, a new QME for testing climate codes for clear and overcast conditions.
6. Participated in the SCM Workshop, October 1999.
7. Participated in the Cloud Working Group Workshop, Dec. 1999.

- *Graduated One Master's Degree Student Supported by this Project*

  Cheng, Zhaohui - Broken Cloud Observations and Parameterizations for Longwave Radiation (Scholarly Paper), Department of meteorology, University of Maryland, College Park, MD (available upon request).

6. Electronic figures with paragraph discussions highlighting current research

Attached with the e-mail is a PowerPoint file - Ellingson.ppt that has 4 figures in the format you desire. Note that the notes section of each slide provides a description of the figures where appropriate. This file is also available at http://metosrv2.umd.edu/~bobe/downloads/

7. Refereed publications submitted and/or published during the current grant FY

Han., D. and R. G. Ellingson, 1999: Cumulus cloud formulations for longwave radiation calculations. *J. Atmos. Sci.*, **56**, 837–851.

Takara, E. and R. G. Ellingson, 1999: Broken cloud field longwave scattering effects. *J. Atmos. Sci.*, **57**, 1298–1310.

Warner, J. X., and R. G. Ellingson, 2000: A new narrow band radiation model for water vapor absorption. *J. Atmos. Sci.* **57**, 1481–1496.

Han, D. and R. G. Ellingson, 2000: An experimental technique for testing the validity of cumulus cloud parameterizations for longwave radiation calculations. *J. Appl. Meteor.*, **39**, 1147-1159.

Stephens, G., R. G. Ellingson, J. Vitko Jr., W. Bolton, T. Tooman, F. P. J. Valero, P. Minnis, P. Pilewskie, G. S. Phipps, S. Sekelsy, J. R. Carswell, S. D. Miller, A. Benedetti, Re McCoy, R. McCoy, 2000: The Department of Energy's Atmospheric Radiation Measurement (ARM) Unmanned Aerospace Vehicle (UAV) Program, Submitted for publication in the *Bulletin of the American Meteorological Society*.

8. Published extended abstracts in the current FY

Ellingson, R. G., 1999: Thermal Radiative Transport in Clouds. International Workshops on Intercomparison of 3-dimensional Radiation Codes:I3RC-99 - First Workshop: 17 - 19 November, 1999, Tucson, AZ.

Ellingson, R. G., and E. E. Takara, 1999: MDTERP MarylanD TErrestial Radiation Package: A Narrow-Band Longwave Radiation Model with a Graphical User Interface. To be published in the proceedings of the EUMETSAT 2000 Users Meeting.

9. Update on the status of submitted referred publications from the previous FY progress report.

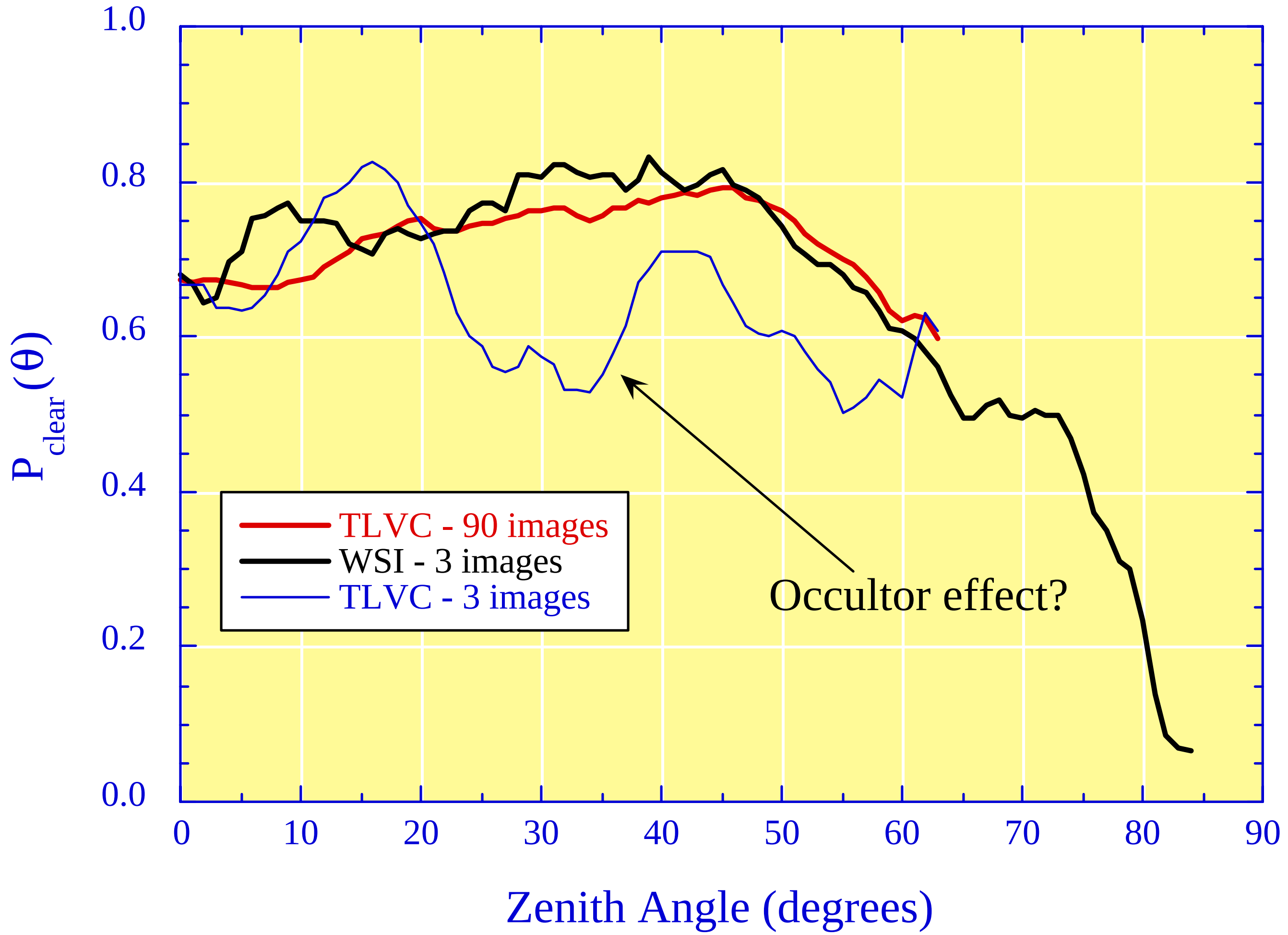
See publication list in 6 above.

(a) TLCV color image with clouds

(b) TLCV clear-sky image.

Examples of TLCV images for clear and broken cloud conditions at approximately the same local time but different days. (a) Broken clouds (5/2/1999); and (b) Clear (5/07/1999).

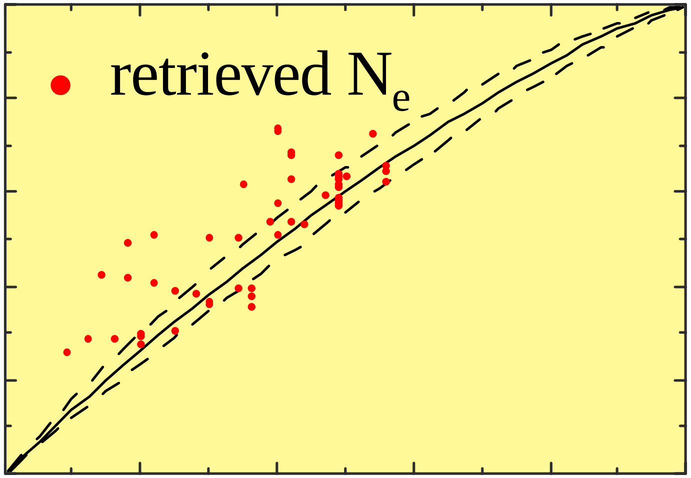
R. G. Ellingson - 2000
University of Maryland College Park

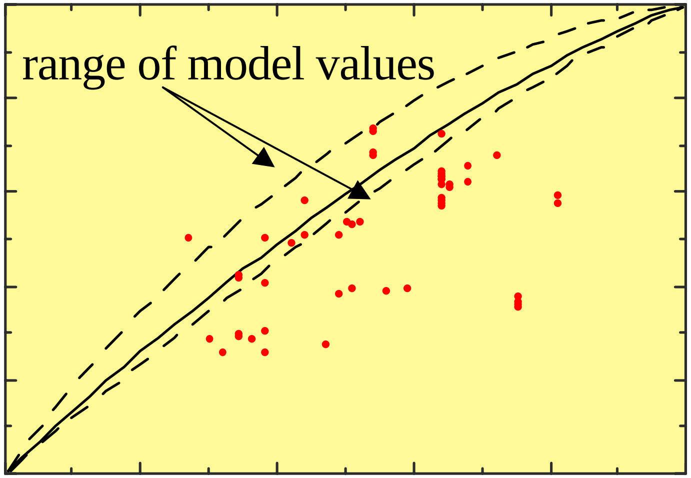


Probability of clear line of sight for the period from on 2 May 1999 determined from three consecutive WSI images (black), 90 consecutive TLCV images (red) and (c) three TLVC images (blue) near the WSI observations times.

R. G. Ellingson - 2000
University of Maryland College Park

Retrieved and Model Calculated Effective Cloud Amounts (N_e) - Good Comparison





Absolute Cloud Fraction - N

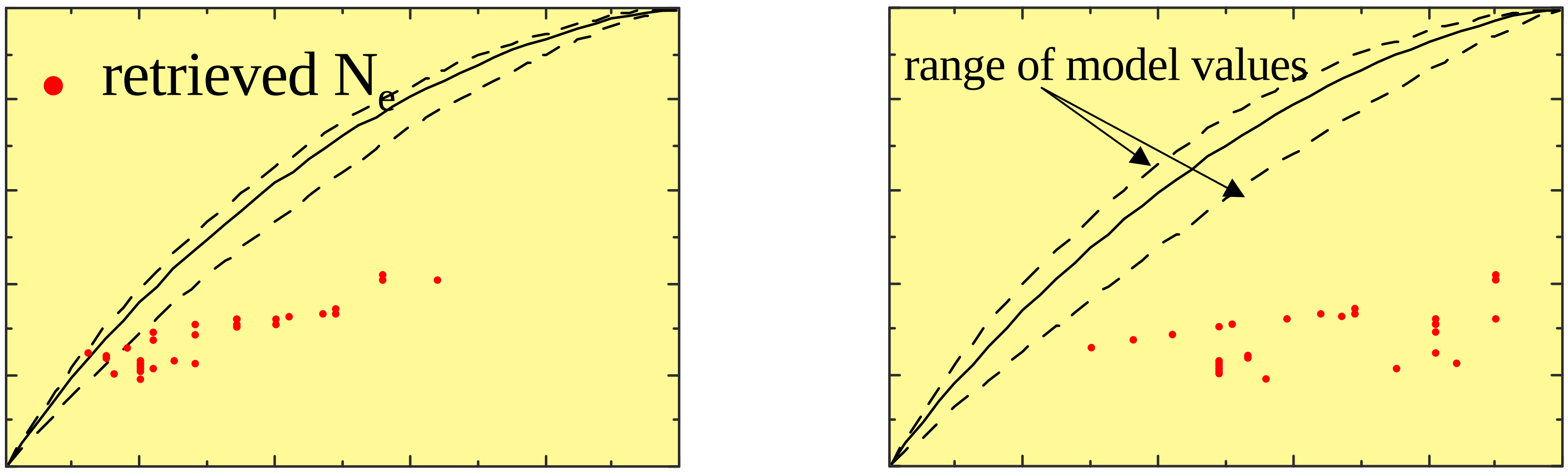
N - from BLC

N - from MMCR

β - cloud aspect ratio

R. G. Ellingson - 2000
University of Maryland College Park

Retrieved and Model Calculated Effective Cloud Amounts (N_e) - Poor Comparison



Absolute Cloud Fraction - N

N - from BLC

N - from MMCR

β - cloud aspect ratio

R. G. Ellingson - 2000
University of Maryland College Park